Quantifying Turbulence in the Coastal Environment

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LONG-TERM GOALS

The long-term objective is to quantify the structure of turbulence in fluvial and estuarine environments, in order to develop remote-sensing tools for environmental assessment as well as to improve numerical simulations.

OBJECTIVES

The objectives of this program are:

- to quantify the turbulence length scale and turbulent dynamics in an estuary under varying stratification conditions and geometries, including relatively uniform boundary-layer flows and highly disrupted wake flow conditions;
- to quantify the key properties of observed coherent structures, including horizontal and vertical scales, intensity of vertical motions,
- to provide a field-scale test of turbulence closure models and large-eddy simulations via direct measures of turbulent kinetic energy, length scale and turbulent dissipation rate combined with accurate measures of the Reynolds-averaged quantities.
- to work with the other COHSTREX investigators to ascertain the relationship between surface signatures of the turbulence and the characteristics of the Reynolds-averaged flow, turbulence, density structure and bathymetry.

APPROACH

The Mobile Array for Sensing Turbulence (MAST) is a 10-m long aluminum structure with 6 sets of instruments for measuring the turbulent quantities and Reynolds-averaged velocity and density at multiple depths. The instrument is deployed off the side of a research vessel (fig. 1), either in

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Figure 1. The MAST mounted on the R/V Centennial in the Snohomish River (June 2006).

underway mode or at anchor. The depths of the sensors are varied by the tilt of the mast, with the sensor spacing 1-1.5 m in the vertical. Turbulence quantities are measured with co-located Seabird SBE-7 micro-conductivity sensors and Sontek ADVs (fig. 1). The stratification is measured with RBR T-S sensors. The spatial resolution of turbulence measurements is 5-10 cm for velocity (limited by the 25 Hz sampling rate of the ADVs and flows past the sensors of 50-100 cm/s), and less than 1 cm for conductivity (effective sampling rate 200 Hz).

The first field deployment of the MAST was the 2006 COHSTREX experiment in the Snohomish River. There were three modes of observation: one was a set of anchored measurements in close proximity to a submerged jetty where Jessup and colleagues collected infrared observations; the second was a 30-hour anchor-station to observe the transitions between unstratified and stratified boundary-layer turbulence in the estuarine channel, and the third mode was a set of along-river and across-river transects of the velocity and water properties.

To date, the analysis of the turbulence quantities follows the appoach of Kaimal et al. (1972), by fitting the velocity and conductivity spectra to universal shape functions, in order to identify the turbulent length scale and to quantify the turbulent kinetic energy (tke) and dissipation rate. The vertical velocity spectrum was found to provide the cleanest fits to the Kaimal spectrum, and most of the length scale analysis focused on the vertical velocity spectrum. With reliable estimates of the turbulent length scale, the turbulent kinetic energy and the dissipation rate, the scaling of turbulence for different flow conditions—unstratified boundary layers, stratified boundary layers, and wakes—could be tested.

WORK COMPLETED

The field work was completeed in Year 1. At the 9-month point of Year 2, the MAST data analysis is essentially complete, and we are preparing a manuscript for publication and working with other COHSTREX colleagues in comparison of the remote-sensing measurements of the boils.

RESULTS

Boundary-layer dynamics

During the 30-hour anchor station, the vertical density stratification varied from well-mixed to strongly stratified as the salt front advected past our location. The dramatic changes in water column stability had a pronounced impact on the turbulent length scale. In figure 2, the Ozmidov scale is plotted against the MAST estimate of the turbulent length scale, where both quantities have been non-dimensionalized by boundary layer scaling. These two quantities show roughly a linear relationship for values on the x-axis less than one, where the Ozmidov scale is smaller than boundary layer scaling. The data asymptote to a value of roughly one where the Ozmidov scale exceeds the distance to the boundary, consistent with traditional boundary layer theory. This result provides a confirmation that

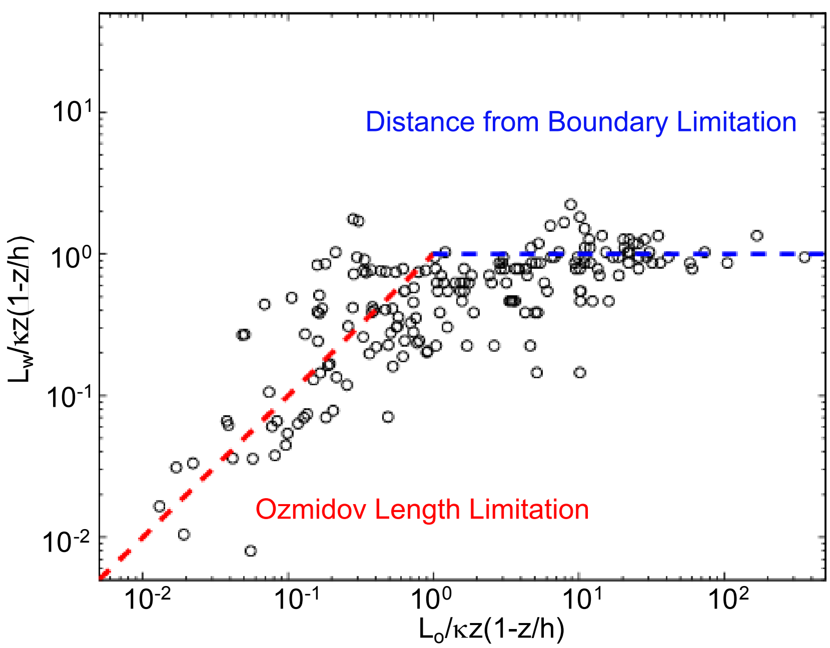

Figure 2. Non-dimensional Ozmidov scale (L_o) vs. non-dimensional estimate of turbulent length scale (L_W) from MAST. Length scales are non-dimensionalized by boundary layer length-scale L_{bbl} $=\kappa z(1-z/h)$. Points along the red line indicate length scale limitation by stratification, whereas the blue line represents boundary-layer scaling of L_w.

the MAST can reliably quantify the turbulent length scale, and it also provides field confirmation for the Ozmidov scaling of the length scale in highly stratified conditions, for which there are few field observations. These observations also allowed a test of the production-dissipation balance. During the 30-hour anchor station, the production of TKE is balanced by dissipation at first order, consistent with the expected balance for a turbulent boundary layer.

Wake Dynamics

The data collected in the vicinity of the jetty provide an excellent contrast to the data collected during 30-hour anchor station. MAST estimates of the turbulent length scales exceed those expected based on boundary layer theory by roughly a factor of 2 (figure 3). Near surface estimates of length scale are in good agreement with estimates obtained from the infrared observations by Jessup and colleagues. Whereas the 30-hour anchor station data are consistent with either Ozmidov or wall layer scaling, the presence of the jetty imposes an additional length scale on the flow, increasing the turbulent length scale relative to the local production scale.

Dissipation rates measured in the wake of the jetty exceed those from the 30-hour anchor station by an order of magnitude, and turbulent dissipation greatly exceeds estimates of turbulent production (figure 4). The energetics of the turbulence are consistent with non-local generation due to the presence of the jetty, with a spatial decay scale of the wake of approximately 100 m based on the magnitude of TKE and ε.

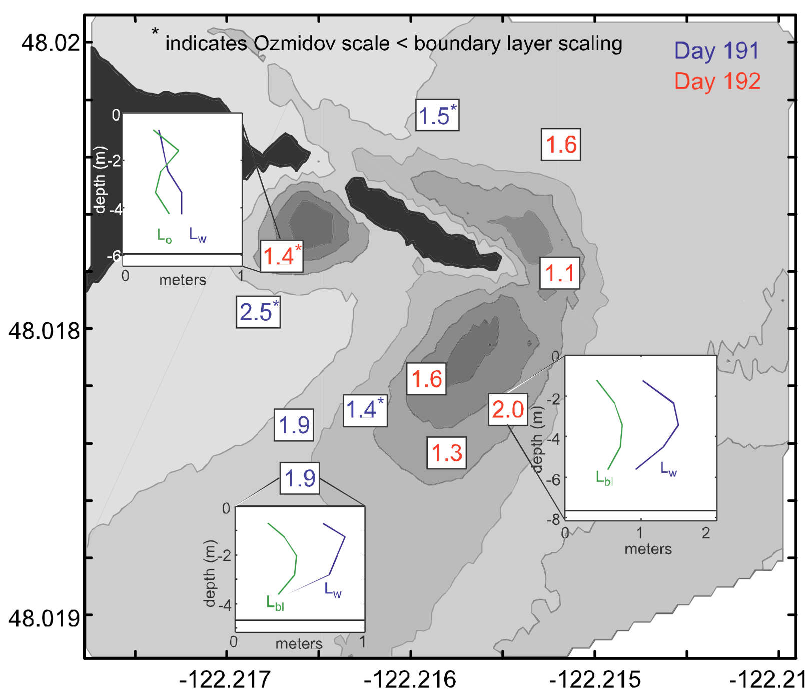

Figure 3. Non-dimensional length scale L_w/L_P, where L_p= min (L_o , L_{bbl}) is the local production scale of turbulence. The asterisks indicate where L_p is set by the Ozmidov scale. Vertical profiles of L_w and L_p are shown for selected stations. The key result is that the turbulence scale exceeds the local scale in all cases, indicating non-local turbulence production and suggesting high anisotropy.

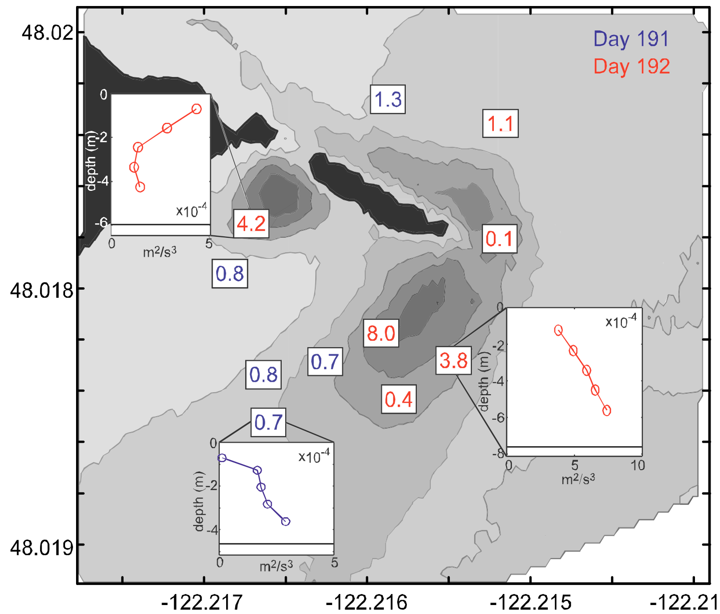

Figure 4. Dissipation measured by the surface ADV ($\times 10^{-4}$) m^2/s^3. Blue numbers indicate stations occupied on day 191 and red numbers were occupied on day 192. Note the highest dissipation rates occur downstream of the sill (during the ebb) in the scour holes. Vertical profiles of dissipation are shown for select stations. The high near-surface dissipation in the upper left profile provides a clear example of the influence of near-surface turbulence advected from the sill.

IMPACT/APPLICATIONS

The MAST provides unprecedented resolution of turbulence length scale and turbulent kinetic energy through the water column in a coastal environment. Whereas microstructure measurements (e.g., Peters, 2001) are effective for estimating dissipation, they provide little information about the energy-containing scales of the turbulence or the total tke. The ability of the MAST to obtain continuous timeseries at fixed levels provides the statistical information required to obtain the information about the outer scales of the turbulence. Tripods are similarly effective, but they are limited to the near-bottom waters. In context with the COHSTREX study, the MAST measurements allow the dynamics of the turbulence to be linked to the remote-sensing observations of its surface manifestation. This link to the turbulence is an important step in the development of methods of quantifying bathymetry, obstructions and flow characteristics based on boil signatures.

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